Supercond. Sci. Technol. **17** (2004) R19–R33 PII: S0953-2048(04)70459-5

TOPICAL REVIEW

Resistive magnet technology for hybrid inserts

Mark D Bird

National High Magnetic Field Laboratory, Florida State University, Tallahassee, FL 32310, USA

Received 14 October 2003
Published 23 June 2004
Online at stacks.iop.org/SUST/17/R19
doi:10.1088/0953-2048/17/8/R01

Abstract
The world's highest-field dc magnets have, for roughly the past thirty years, consisted of resistive-superconducting hybrid magnets. These magnets use superconducting technology for the outer coils, where the magnetic field is moderate, and resistive-magnet technology for the inner coils, where the field is highest. In such a configuration, higher fields are attained than is possible with purely superconducting magnet technology, and lower lifetime (capital and operating) costs are attained than with a purely resistive magnet. The resistive coils of these magnets represent the pinnacle of high-field resistive-magnet technology and have been the focus of much of the resistive magnet technology development over the past thirty years. The evolution of high-field resistive magnet technology is presented, focusing on the development of hybrid inserts.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

The highest-field dc magnet in the world provides a flux density of 45 T in a 32 mm bore to researchers at the National High Magnetic Field Laboratory (NHMFL) in Tallahassee, Florida. The magnet is a resistive-superconducting hybrid using cable-in-conduit-conductor (CICC) technology for the superconducting outsert and Florida–Bitter technology for the resistive insert. This magnet is the most recent in a series of hybrid magnets built worldwide to provide very intense magnetic fields (figure 1) [1].

Users of high-field magnet facilities want high flux densities for experiments in condensed-matter physics and other subjects. Presently, niobium-based superconductors have critical fields up to about 25 T, and the highest-field superconducting magnets built to date attain fields up to 23.4 T [2]. To provide higher fields, resistive magnet technology is required. To date, resistive magnets have been built attaining fields up to 33 T dc [3]. Short pulse (10–20 ms), non-destructive magnets have attained fields in the 70–80 T range [4], and 100 T magnets are being built [5]. Destructive pulsed magnets have attained fields up to ~2800 T during pulses of several microseconds [6].

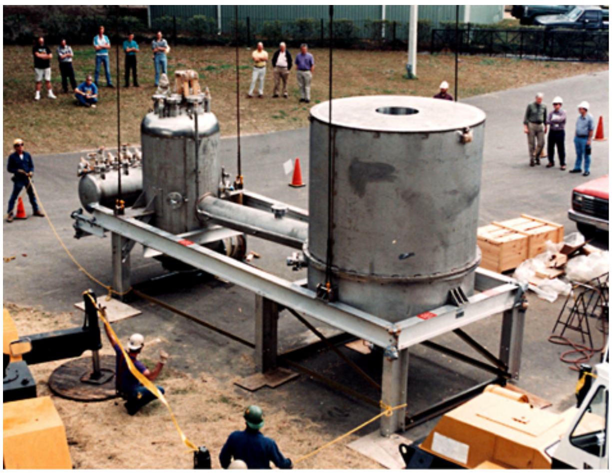

Figure 1. Arrival of 45 T hybrid magnet cryostat at the NHMFL.

Although pulsed magnets provide the most intense fields, many experiments require more than a few milliseconds of applied field. To the dc field that can be attained with purely

Table 1. Hybrid magnets built to date. (Notes: The various laboratories do not necessarily label their hybrid magnets as shown here. Sendai, for example, refers to its hybrids as 3, 2 and 1, in the order of construction.)

Name	Total field (T)	Bore (cm)	Power (MW)	SC field (T)	Insert alloying material	Year	Insert technology
			1st generation				
MIT I	20	3	5	5.8	0.5% Be	1972	Axial-Bitter
McGill	25			15	Al[a]	1972	Cryogenic
Oxford Ia	16	5	2	6.5	0.05% Ag	1973	Polyhelix
Moscow	25	3	6	6.3	Cr	1973	Radial-Bitter
			2nd generation				
Nijm Ia	25	5	6	8.5	Mg, Zr, Cr	1977	Axial-Bitter
Nijm Ib	30	3	9		Al_2O_3, SS	1977	Radial-Bitter
MIT IIa	30	3	9	7.5	Al_2O_3, SS	1981	Radial-Bitter
MIT IIb	25	5	8		SS 301	1981	Axial-Bitter
Sendai I	20	3	3	8	Al_2O_3	1983	Axial-Bitter
Sendai II	24	5	7	8	Al_2O_3	1984	Axial-Bitter
Sendai IIIa	31	3	7	12	0.05% Ag	1985	Polyhelix
Sendai IIIb	27	5	7		0.05% Ag	1985	Polyhelix
Oxford Ib	20	3	2		Pure Cu	1987	Polyhelix
Nijm IIa	30	3	6	10.5	Al_2O_3, SS	1985	Radial-Bitter
Grenoble I	31	5	10	11	0.05% Ag	1987	Polyhelix
MIT Iic	31	3	9		Be, Cr, Al	1989	Monohelix
Hefei	20	3	3	7	Al_2O_3	1992	Axial-Bitter
			3rd generation				
MIT IIIa	34	3	9	13	Be, Nb	1991	Monohelix
MIT IIIb	35	3	9		24% Ag	1994	Radial-Bitter
TML Ia	36	3	15	15	Al_2O_3	1995	Polyhelix
TML Ib	32	5	15		Cr	1996	Polyhelix
TML Ic	31	5	15		24% Ag	1998	Florida–Bitter
TML Id	37	3	15		24% Ag	1999	Florida–Bitter
Sendai IIId	30	3	7	11	24% Ag	1999	Florida–Bitter
Sendai IIIe	27	5	7		24% Ag	1999	Florida–Bitter
NHMFL Ia	45	3	26	14	24% Ag	1900	Florida–Bitter
NHMFL Ib	45	3	30	11.4	24% Ag	1901	Florida–Bitter
			New developments				
Sendai IV	23	3	8		24% Ag	2002	Florida–Bitter
TML Ie	38	3	15		24% Ag	2002	Florida–Bitter
Grenoble II	40	3	24	8	Zr	2003	Polyhelix
NHMFL Ic	50	3	40	14			Florida–Bitter
NHMFL II	35	5	10	14			Florida–Bitter
Nijm IIb	40	3	20	10			Florida–Bitter
BNL	20	15	12	14			ICC

[a] The McGill insert was pure aluminium, not a Cu–Al alloy.

resistive magnets, there is no fundamental technological limit, only a financial one. The cost of the power consumed and the capital cost of the power supplies and cooling systems required for a dc resistive magnet increase faster than the square of the field produced. Consequently, for the highest-field dc magnet systems, a resistive-superconducting hybrid magnet is usually selected. In this configuration, superconducting technology is used for the outer coils, where the field is modest (up to about 15 T), and resistive technology is used for the inner coils, where fields exceed the practical limits of superconducting technology. In this way, the life-cycle costs of the system (capital plus power consumption) can be kept lower than would be possible with a purely resistive system [7].

Over a dozen hybrid magnets have now been installed at facilities worldwide, with the most prominent ones listed in table 1. At each laboratory, different hybrid outserts are labelled with Roman numerals, while different resistive inserts that fit in the same outsert are distinguished with letters. Thus, Grenoble I and Grenoble II designate two different hybrid outserts in Grenoble, while MIT IIa and MIT IIb designate two different inserts for the same outsert at MIT. At most of these facilities the resistive insert of these hybrids is the most advanced of various resistive magnets installed; hence much of the resistive magnet technology development activity at the laboratories is directed toward higher-field resistive inserts for the hybrid.

This article consists of seven sections. After this introduction, we begin by explaining the fundamentals of hybrid insert design and the challenges that the designer faces as he selects a technology and begins his work. We then devote one section to each of the three generations of hybrids built to date: 1972–1975, 1976–1989 and 1990–2001. Within each of these three main sections we first describe the new technologies that characterized that generation of magnets, i.e. Bitter, polyhelix, monohelix, Florida–Bitter, etc. Then we list the various magnets built in that generation and describe

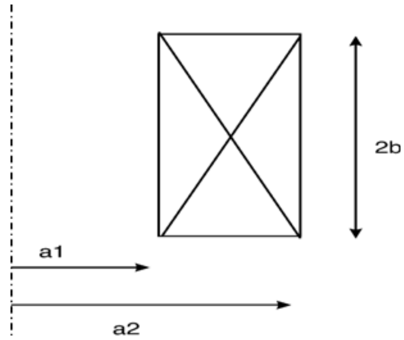

Figure 2. Generic solenoid providing vertical field on the axis.

their unique features. Afterwards there is a section on hybrids presently being constructed, in design, or being proposed. Finally, there are conclusions and commentary on the future.

2. Resistive solenoid design basics

To appreciate the comparative advantages of the various technologies, one must have some comprehension of the challenges facing a resistive magnet designer. Hence, we start with a brief diversion into resistive magnet design prior to describing the various solutions that have been chosen.

2.1. Electromagnetism

Various authors have described the electromagnetic aspects of resistive solenoid design. An excellent reference on the subject is [8]. A brief summary is presented here. In a resistive solenoid, the current density in a conductor is not uniform over the cross section; rather it is inversely proportional to the radius of curvature. For Bitter or monohelix coils, this is an important feature; for polyhelix designs, it is not, because the constriction is not thick in the radial dimension. Consider a coil as shown in figure 2. We define the inner radius as a_1, the outer radius as a_2 and the half-length as b.

We define dimensionless size parameters α and β given by a_2/a_1 and b/a_1, respectively. One can compute the field at the centre of a coil as:

$$B = j_1 \lambda \mu_0 a_1 F_B(\alpha, \beta). \tag{1}$$

Here j_1 is the current density at the inner radius of the coil, λ is the overall coil space factor or packing factor (to account for cooling holes, insulation, etc) and μ_0 is the permeability of free space. The Fabry factor, F_B, is given by:

$$F_B = [\sinh^{-1}(\beta) - \sinh^{-1}(\beta/\alpha)]. \tag{2}$$

The power consumed by the shown coil can be given by:

$$W = j_1^2 \rho \lambda a_1^3 4\pi\beta \ln\alpha. \tag{3}$$

Here W is the power consumed and ρ is the electrical resistivity. We can then eliminate the current density from the previous two equations and solve for flux density as a function of power, space factor, etc, to get:

$$B = \mu_0 G(\alpha, \beta)(W\lambda/\rho a_1)^{1/2}, \tag{4}$$

where $G(\alpha, \beta)$ is a dimensionless function of the coil geometry alone given by:

$$G(\alpha, \beta) = 0.5[\sinh^{-1}(\beta) - \sinh^{-1}(\beta/\alpha)](\pi/\beta\ln\alpha)^{1/2}. \tag{5}$$

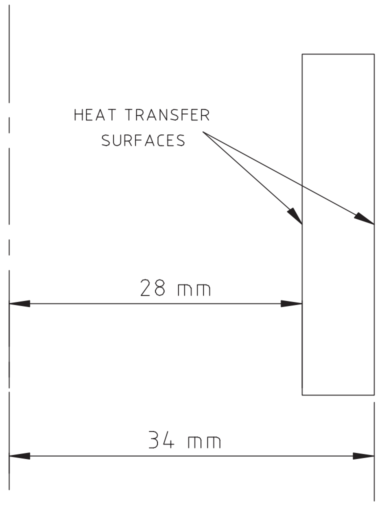

Figure 3. Section of the high-current-density resistive conductor. The axisymmetric conductor carries current and is cooled at the inner and outer radii.

2.2. Cooling

One of the factors that limits the performance of high-field resistive magnets is the ability to accommodate the power densities associated with high current densities. Both the conductors and insulators that make up a high field magnet show reduced performance at elevated temperatures. The heat-transfer coefficient h between the conductor surface and turbulent flowing water is dominated by a term of the form:

$$h = Av^p, \tag{6}$$

where v is the water velocity, p is near unity and A is constant [9]. While there is a great deal of debate about the values of A and p and what other terms may be relevant, most agree p lies between 0.8 and 1.0. Hence, increasing water velocity results in a higher heat-transfer coefficient, at least until the onset of cavitations [10].

Let us assume we are going to limit the peak temperature in the magnet to 100 °C. Let us also assume that the water enters the magnet at 10 °C. We will further assume that we can attain heat transfer coefficients of 0.232 W mm^{-2} °C^{-1}. Let us compare three coils, running at the same current density, that consist of thin rings of conductor cooled at both the inner and outer radius (polyhelix, or Florida–Bitter construction: see sections 3.3 and 5.1 below), as shown in figure 3. We will further assume that the inner radius of the coil is 28 mm and the outer radius is 34 mm, and that the coil has an average current density of 400 A mm^{-2}.

2.2.1. Case 1: Cu conductor, 6 mm wide. Pure copper has an electrical resistivity of 17.2 nΩ m at 20 °C. Its resistivity also increases 0.4% °C^{-1} [10]; if the coil's average temperature is 70 °C, then the resistivity of the copper is 20.0 nΩ m. The average power density is given by the product of the resistivity and the square of the current density, that is, 3.2 W mm^{-3}. If we assume that the heat fluxes are equal at the inner and outer radii, then we have a heat flux of 9.6 W mm^{-2} at each cooling surface. With the heat transfer coefficient mentioned previously, this gives us a boundary-layer temperature rise of

Table 2. Comparison of thermal parameters of Cu and Cu–Ag coils.

Case	1	2	3
Material	Cu	CuAg	CuAg
Turn thickness (mm)	6	6	1
Electrical resistivity at 20 °C ($\mu\Omega$ mm)	17.2	23.6	23.6
Electrical resistivity at 100 °C ($\mu\Omega$ mm)	23.4	32.1	32.1
Thermal cond. (W mm^{-1} °C^{-1})	0.40	0.29	0.29
Current density (A mm^{-2})	400	400	400
Heat transfer coefficient (W mm^{-2} °C^{-1})	0.232	0.232	0.232
Inlet water temperature (°C)	10	10	10
Water temperature rise (°C)	20	20	20
Field (T)	30	30	30
Power density (W mm^{-3})	3.74	5.14	5.14
Heat flux (W mm^{-2})	11.2	15.4	2.57
Boundary layer temperature rise (°C)	48	66	11
Conduction temperature rise (°C)	42	80	2.2
Maximum surface temperature (°C)	**78**	**96**	**41**
Hot spot temperature (°C)	**117**	**176**	**43**
Hoop stress (MPa)	**372**	**372**	**372**
Yield stress (MPa)	**400**	**700**	**700**

41 °C. Thus the edge of the copper conductor, at the water inlet, is operating at 51 °C. If the water temperature rise in the coil is 30 °C, then the edge of the conductor at the water exit is 81 °C.

We can solve the diffusion equation in one dimension to get the temperature distribution across the conductor. If we ignore curvature, we get $T(x) = T_0 + 0.5(L - x)xq/k$, where q is the power density, k is the thermal conductivity (0.40 W mm^{-1} °C^{-1}), L is the length of the uncooled section (6 mm) and x is the distance from the edge of the conductor [11]. The temperature rise at the midpoint of the conductor is then $0.5 \times 3 \times 3 \times 3.2/0.4 = 36$ °C. Thus, the peak temperature is $36 + 81 = 117$ °C, as shown in the first column of table 2.

2.2.2. Case 2: Cu–Ag conductor, 6 mm wide. Now let us assume that the conductor of choice is the high-strength, high-conductivity alloy developed by Sakai [12]. This material has much higher strength than pure copper (850–1000 MPa, versus 400 MPa) but also has higher electrical resistivity (23.6 nΩ m at 20 °C). In addition, its thermal conductivity is only about 0.29 W mm^{-1} °C^{-1}. Repeating the previous example with these different electrical and thermal conductivities gives a peak temperature of 176 °C, as shown in the second column of table 2.

2.2.3. Case 3: Cu–Ag conductor, 1 mm wide. Now let us consider a copper–silver conductor that is only 1 mm wide. We see that the peak temperature is reduced to 43 °C, as shown in the third column of table 2.

We see that the surface of the 6 mm thick copper–silver coil is approaching the boiling point of water and that the peak temperature (176 °C) is high enough to raise questions about the lifetime of the insulation and conductor. The 6 mm thick copper coil has a peak temperature of 120 °C, conceivably reliable, but higher than we would like. In contrast, the 1 mm thick Cu–Ag coil has very modest temperatures and heat fluxes. With this sort of construction, current densities above 700 A mm^{-2} and power densities above 13 W mm^{-3} have been attained [13].

While the above calculations are rather crude (one can get an exact solution in polar coordinates that is more accurate), the basic concerns associated with cooling are illustrated here. To accommodate high power densities, one needs closely spaced cooling channels!

2.3. Stress

Whenever current moves though a magnetic field, a force (Lorenz force) is created perpendicular to both, given by $\boldsymbol{F} = \boldsymbol{j} \times \boldsymbol{B}$. If one has an isolated thin ring of conductor carrying current in a plane perpendicular to a uniform magnetic field, the hoop stress is $\sigma = jBr$ [14]. Using this formula, we compute the hoop stress in the three cases presented earlier and present them in table 2. As mentioned above, the yield strength of pure copper can be as high as 400 MPa. Hence the coil in case 1 would be operating at 93% of yield strength. Cu–Ag alloy has yield strength between 700 and 1000 MPa. Thus, coils 2 and 3 would be operating at between 34% and 53% of yield.

2.4. Fault forces

When a magnet fails, there are fault scenarios in which the magnet is no longer symmetric about its mid-plane. If the magnet consists of multiple nested coils, such a fault scenario leads to large axial forces on some or all of the coils. In a hybrid magnet, this possibility is of paramount concern, as the large forces can result in a dangerous situation. In addition, building a hybrid outsert that is able to withstand large fault forces may result in larger conduction heat loads on the cold mass than one would like [15].

There are two basic approaches that can be taken to address this issue. One is to restrain the coils by a stiff, strong structure [16]. The other is to allow the coils to move, thus reducing the large force [17]. The first option requires a substantial structure inside the resistive magnet housing that can be complicated to design, adds to the cost and may reduce the field. The second option requires providing space for not only the coils, but also the rest of the electrical and hydraulic circuits to move several inches without failure.

2.5. Comparison of magnet designs

Various magnet designers have compared the ‘efficiency’ of different magnet designs by computing $B(a_1/W)^{1/2}$ for various magnet designs (see equation (4)). This comparison is valid for low-field magnets. For example, if two low-field magnets of the same power and different bores are to be compared, their fields should be inversely proportional to the square root of their respective radii [18].

However, for high field magnets (above ∼15 T), it is not so easy to compare different designs. As the field goes up, the assumptions of Montgomery’s analysis are violated. In particular, one is no longer able to do unconstrained optimization but must design the magnets to accommodate limits on structural stress, temperature, power density, etc. To accommodate these constraints, the magnet designer frequently subdivides the magnet into multiple coils. In addition, the various coils may use different materials with different electrical resistivity and space factors. Thus, while each coil still roughly obeys equation (4) (except that resistivity changes with temperature), the overall magnet is not well characterized by it. Thus it becomes difficult to compare various magnets via the simple scaling law. The higher field magnets will have higher resistivity and lower space factors, so their 'efficiencies' will suffer. Weggel has claimed that once these constraints are included, the field is not proportional to the second root of power, but to less than the third root! [19].

3. First generation hybrids: prior to 1975

The first generation of hybrid inserts described below constitutes low-field (16–25 T), low-power (2–6 MW), low-current-density magnets, some of which never served their intended purposes. The inserts used Bitter, polyhelix and radial-Bitter technologies as described in the following sections. In retrospect they may be thought of as 'pioneers' for the systems to follow.

3.1. Early resistive magnet technology

To understand the improvements in resistive solenoid technology that have evolved over the years, it is important to start at the beginning. In the early 1900s researchers began developing high field resistive magnets using ribbon coils [20] and hollow conductors (also called internally cooled conductors).

A ribbon coil is made from a strip or ribbon of conductor that is wound into a spiral with insulation between turns. A common way to provide cooling is by machining or rolling grooves across one side of the conducting strip. A sheet of insulating material can then be laid on the ribbed conductor and the two are co-wound into a spiral. In this way, turns are isolated from each other, and coolant can be pumped through the grooves. Using such a technique, Kolm attained 12.6 T in a 25 mm bore [21].

A hollow conductor consists of a thick-walled copper pipe coated or wrapped with insulation. The conductor is either layer-wound or pancake-wound into a solenoid and connected to a power supply and a cold-water pump. Current is driven through the copper; water pumped through the inside of the pipe provides cooling. With this technology, fields up to 10 T were attained [22, 23].

Various features limited these technologies, particularly the stress in the conductor [24]. While a hollow conductor is still used in low-field resistive magnets for beam-lines and the like, neither ribbon nor hollow-conductor technology has been used for a hybrid insert, although it has been proposed [25].

3.2. Bitter technology

In 1936, Francis Bitter of the Massachusetts Institute of Technology tested his first of a new type of magnet that set a new standard for high-field systems. His main goals were to shorten the hydraulic path in the magnet and to increase the strength of the coil. Instead of using the traditional copper pipe, he used slit disks made from copper sheet. He then stamped round holes in the disks and stamped similar disks

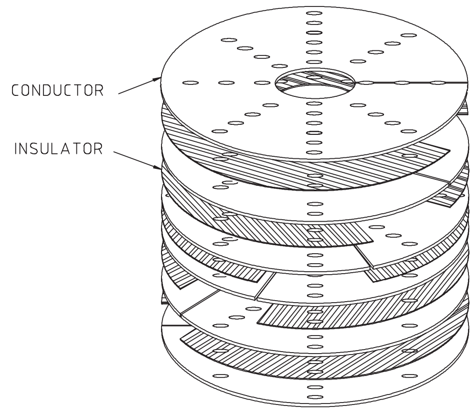

Figure 4. Schematic of a Bitter magnet showing alternate conductors and insulators (shaded). Notice that the adjacent conducting disks make contact in a region of overlap.

from an insulating sheet (figure 4). While the conductors typically made a complete circle (360°) the insulators would have a sector missing. Alternately, one stacks conductors and insulators to make a helical structure. The cooling holes of the conductors and insulators can be of very small cross section and rather short length and are kept aligned by tie-rods (not shown) [26, 27].

Other advantages of this construction compared with the earlier technologies are its strength and stiffness. In a moderate-field solenoid, the dominant forces are the Lorenz forces associated with a hoop current and an axial field. These result in a radial component of Lorenz force ($F_r = j_\theta \times B_z$). The radial Lorenz force results in hoop and radial stresses in the solenoid. In a hollow conductor, these radial stresses are transmitted (reacted) through the insulating material that isolates each layer from its neighbour.

In the Bitter magnet, these radial loads are transmitted purely through the copper, which is structurally both stronger and stiffer than most insulating materials. With this construction, Francis Bitter was the first person to attain 10 T [27], a record that would stand for twenty years. In addition, he established a technology that, with refinement, would be used by most high-field resistive magnet designers and that would be the basis for today's dc fields up to 45 T.

3.2.1. Stresses in Bitter disks. The stress in a Bitter disk is not as simple as in an unsupported ring of the conductor discussed earlier. As this is one of the crucial issues in high field resistive solenoid design, it merits further, detailed discussion.

Mid-plane Bitter disks: nominal. Figure 5 shows a free-body diagram of a sector of a Bitter disk at the mid-plane of a coil remote from any slits. Current flows in the hoop (θ) direction. The field vector is in the axial (z) direction. The Lorenz forces are distributed over the disk in the radial direction (f_r). The inner and outer radii of the disk are traction-free. Symmetry tells us there is no shear stress on the straight sides of the sector. The sector is held in equilibrium by hoop stresses ($\sigma_{\theta\theta}$) on the straight sides of the sector. The hoop stress at the inner edge has been computed by Weggel [28], ignoring stress concentrations

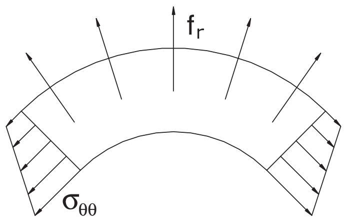

Figure 5. Free-body diagram of a typical mid-plane Bitter disk sector.

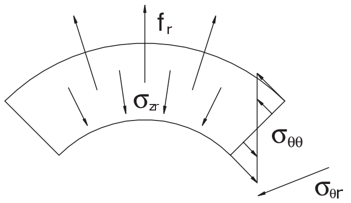

Figure 6. Free-body diagram of the mid-plane disk sector near the slit.

near the cooling holes, to be

$$\sigma = \frac{1}{2}\frac{j_1}{\lambda}a_1(K_1B_1 + K_2B_2), \tag{7}$$

where B_1 and B_2 are the flux density at the inner and outer radii of the disk, respectively, and K_1 and K_2 are geometric factors:

$$K_1 = (1+\nu)\left(\frac{\alpha^2\ln\alpha}{\alpha^2-1}\right) + (1-\nu)\left(\frac{1}{2\ln\alpha} - \frac{1}{\alpha^2-1}\right), \tag{8}$$

$$K_2 = (1+\nu)\left(\frac{\alpha^2\ln\alpha}{\alpha^2-1}\right) - (1-\nu)\left(\frac{1}{2\ln\alpha} - \frac{\alpha^2}{\alpha^2-1}\right). \tag{9}$$

To compare stresses with our previous example, consider a copper Bitter coil with 400 A mm^{-2} at the inner edge with an inner radius of 28 mm and an outer radius of 78 mm. The space factor is 0.8; the field at the inner edge is 30 T, the field at the outer edge is 20 T. The stress at the inner edge of the coil, using Weggel's expression, is then 55% higher than what was seen previously for the isolated conductor. The reason for this difference is that in the Bitter coil (as in many thick solenoids) the outer part of the coil is trying to move outward more than the inner part. Thus the outer part pulls the inner part along with it. Hence, the stress at the inner radius of the thick coil is higher than it would be for an isolated conductor of the same current density operating in a uniform field.

Mid-plane Bitter disks: slits. The previous section computed the hoop stress at the inner edge of a Bitter disk away from any of the slits. Near the slit, the same analysis does not apply. Figure 6 shows a free-body diagram for this case. Here there is, again, a radial Lorenz force (f_r), but there is no hoop stress on the slit edge of the sector. Hence the sector is held in equilibrium by shear stress on the un-slit side ($\sigma_{\theta r}$) as well as shear stress against neighbouring disks (σ_{zr} and $\sigma_{z\theta}$). Solenoids have a radial field component near their ends. This component interacts with the hoop current to give an axial clamping force that is substantial (~80 MPa) at the mid-plane. Here, friction is likely sufficient to hold the end of the disks in place [29].

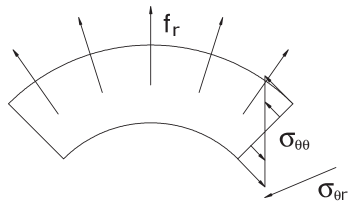

Figure 7. Free-body diagram of the coil end.

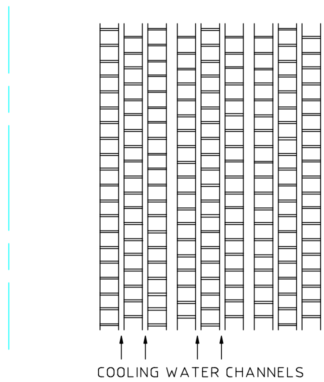

Figure 8. A polyhelix magnet consists of multiple slender coils with cooling water passages between the coils.

Coil ends. At the end of the coil the situation is different. Figure 7 shows the free-body diagram. Again there is a radial Lorenz force. Again, there is no hoop stress on one side of the sector. Here, the axial clamping is much smaller than it was at the mid-plane. Hence the axial components of shear stress (σ_{zr} and $\sigma_{z\theta}$) may be negligible. In this case, there must be a substantial bending moment in the disk to maintain equilibrium of this sector; i.e. the hoop stress is tensile at the inner edge and compressive at the outer edge. This phenomenon was recognized, to some degree, as early as 1970, when Carden went to great lengths to hold the end of his 30 T Bitter magnet [29]. It was also noted in 1972 by Mulhal, as he described 20 T Bitter magnets [30]. The first full analytical treatment of it was published in 2002 [31].

3.3. Polyhelix technology

A polyhelix magnet consists of several nested coils, each of which is a single-layer helix with cooling water flowing between the individual coils (figure 8). Turns are insulated from each other in a variety of ways. The inner and outer diameters of each coil are typically in direct contact with the cooling water. Spacers between coils may or may not be provided.

In 1936 this technology was briefly described by Bitter [26]. In 1959 Bettis described a polyhelix magnet at Oak Ridge National Laboratory [32] with insulating sleeves between coils. In 1960 Giauque and Lyon selected the polyhelix approach for a 10 T magnet at the University of California at Berkeley to attain a more predictable relation between current and field than might be expected with a Bitter magnet. They took the novel approach of using kerosene as a coolant and used vulcanized bone rubber strips to keep the coils insulated from one another [33]. In 1961 Wood selected the polyhelix approach for a magnet at the Clarendon

Laboratory, Oxford, as it was better suited to match the high output impedance of his power supply than a Bitter magnet would be [34].

The polyhelix technique was later used by Carden at the Australian National University in setting a record field of 29.3 T in a 50 mm bore in 1971 [35]. Unfortunately, the magnet was of limited utility, because its homopolar power supply could deliver only a limited amount of energy, and so the magnet could maintain its field for only a few seconds. Carden selected the polyhelix primarily to reduce the hoop stress at the mid-plane (section 3.2.1).

Carden also developed the idea of dividing a magnet into two concentric zones. The design of the outer zone would be dictated by electromagnetic efficiency; Bitter coils serve well in this capacity. The inner zone would be stress limited and designed so that each coil had the same fraction of yield or ultimate stress [36].

In addition, he provided alignment of the various helices by machining axial cooling channels in the outer diameter of each helix. By also cutting a helical groove on each coil that matched the pitch of the helix, adjacent coils operating electrically in parallel could be in direct contact with each other [37].

Schneider-Muntau later improved the polyhelix concept by machining the outer diameter of each coil to be a rough surface with high heat transfer coefficient. He was able to eliminate the need for the coils to bear upon each other by holding them at the ends with a cross. In addition, he used glass spheres in the inter-turn epoxy to provide uniform spacing [38]. He also developed novel fibreglass insulating cylinders with axial ribs to separate coils that were electrically in series [39]. These design concepts were eventually incorporated in hybrid inserts in Grenoble, France, Sendai, Japan and Tsukuba, Japan.

Schneider-Muntau and Prestemon improved upon the optimization concepts by defining a third zone inside the stress limited one. In this zone the constraint was not stress but temperature; the current density was selected to provide uniform peak temperature. In addition, they suggested using slender 'poly-Bitter' coils for these innermost coils, to provide enhanced cooling compared to the traditional polyhelix [40].

Joss eventually led the design and construction of polyhelices in Grenoble using this three-zone concept, while also introducing axial current density grading to increase the electromagnetic efficiency [41].

3.4. *Radially cooled Bitter technology*

In the 1960s, Montgomery at the National Magnet Laboratory at MIT started building high field magnets using copper-alloy disks without axial cooling holes. Instead, radial channels were etched into the disks. The water then could flow from the inner edge to the outer or vice versa. Alternatively, all the water headers could be located at the outer the edge with water flowing inward in some quadrants and outward in others [24].

Figure 9 is a photo of a radially cooled disk designed by Weggel at the Francis Bitter National Magnet Laboratory. Originally, this technique was developed for and used in magnets whose geometry suggested radial cooling. For example, in a split pair of coils, it is convenient to not have cooling water passing through the gap. In this case, a radially cooled coil is a logical development. Another example is that of a very long resistive coil designed for high field uniformity for NMR measurements. In this case, radial cooling provides shorter channels and more uniform temperature than would axial cooling [42].

Figure 9. Radially cooled Bitter disk designed by Weggel.

It was soon realized that radial cooling also facilitates very short distances between cooling surfaces which, in turn, facilitates the high current densities in high-strength materials required for very high fields (section 2.2). In addition, one can taper the width of the cooling channel from the inner diameter to the outer diameter (wider at the OD). With such a construction, the water velocity can vary through the coil, to be higher in the high-power-density areas than in the low-power-density areas. Hence, this configuration was later adapted to high-field solenoids even where the geometry did not require radial cooling [42].

This technology was eventually used in hybrid inserts in Cambridge, USA, Moscow, Russia and Nijmegen, The Netherlands.

3.5. *First generation inserts: 1972–1973*

3.5.1. MIT I. The idea of combining superconducting and resistive magnet technologies to build a hybrid magnet is widely credited to Wood and Montgomery, who proposed the concept in 1965 [7]. In 1972 the Francis Bitter National Magnet Laboratory (Massachusetts Institute of Technology, Cambridge, MA, USA) completed the first hybrid magnet.

The outsert was designed by Leupold, Iwasa and Montgomery to provide 6 T with a 400 mm inner diameter and consisted of 24 ventilated double pancakes made from untwisted NbTi wire. Unfortunately, this was prior to the recognition of the necessity of filament transposition, and so the magnet generated full field only once, before its incorporation into the hybrid system [43].

The first insert, designed by Weggel and Montgomery, used two axially cooled Bitter coils in parallel and provided 15 T (19.5 T total) using 5 MW of power. The inner coil used copper strengthened with various alloying elements including: 0.5% Be, Mg–Zr–Cr–Cu, Cd–Cu and Zr–Cu. The outer coil was pure copper. Various later inserts used different coil configurations and materials to provide slightly higher fields [43, 44].

3.5.2. McGill. The 25 T magnet built at McGill University consisted of an outsert providing 15 T using both NbTi and Nb_3Sn ventilated pancakes.

The insert used high-purity aluminium cooled to 8 K. The magnet destroyed itself with current of the wrong polarity, and no other inserts have been built using cryo-coil technology [43–45].

3.5.3. Oxford Ia. The first hybrid magnet to serve its intended purpose was the 16 T version completed in the Clarendon Laboratory at Oxford University in 1973. It is labelled Oxford Ia in table 1. The outsert was designed and built by Oxford Instruments and consisted of 46 pancakes of stabilized NbTi with an engineering current density of 63 A mm^{-2}. It provided 6.5 T with a 284 mm inner diameter.

The insert was designed and built by Carden of the Australian National University and Research Technology, Canberra. It was based heavily upon his earlier 30 T very long pulsed polyhelix magnet [35]. It consisted of 10 polyhelix coils in six electrically serial groups. Each coil was 100 mm long with 40 turns. Radial thickness ranged from 2 to 16 mm. Material was silver-bearing copper ($\sim$0.05%). Substantial effort was made to address the end turn issues and to provide the proper power distribution in the parallel connections. The insert provided 9.5 T for a total of 16 T in a 50 mm bore with 2 MW of power [46].

3.5.4. Moscow. A team led by Cheremnykh and including persons from the Kurchatov Atomic Energy Institute (KAEI) and the Efremov Scientific Research Institute of Electrophysical Apparatus jointly designed and built a 25 T hybrid that was installed at the KAEI and tested in December 1973 [47]. The outsert consisted of 25 ventilated double pancakes of NbTi and NbZr multifilamentary strip. It provided 6.3 T with a 376 mm inner diameter.

The insert design was led by Rogdestvenskij and consisted of two series-connected radially cooled Bitter coils. It provided 18.4 T, for a total of nearly 25 T in a 28 mm bore, using 6 MW of power. The inner coil was of 'chromium-bronze'; the outer coil used pure copper [48, 49]. This magnet was designed with the unusual feature of welding each disk of the Bitter coil to its nearest neighbours to avoid the 'slit effect'. In this way, it was a predecessor of the mono-helix technology to appear later [47].

4. Second generation hybrids: 1978–1987

We see that all the major challenges associated with attaining high dc fields were being discussed by the early 1970s. The following three decades have largely seen different approaches attempted to overcome them. Of course, the biggest challenge frequently is obtaining funding for these endeavours.

The second generation of hybrid magnets followed the first after a lull of about five years. This generation is characterized by higher power (7–10 MW) and the development and proliferation of 30 T truly dc systems using Bitter, radial-Bitter, polyhelix and the new monohelix technology described next.

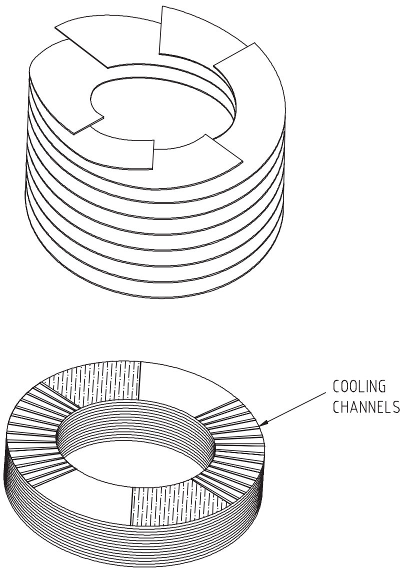

Figure 10. A monohelix consists of multiple helical conductors in parallel with radial cooling channels.

4.1. Monohelix technology

The monohelix magnet technology attempts to combine some aspects of the polyhelix and radial Bitter technologies. It is typically made from a solid bar, which is machined by lathe or by wire EDM into a complete helix (figure 10). Radial cooling channels are provided either by cutting into the helix or by inserting radially cooled Bitter disks or by using insulating sectors. With such a construction, the radial slits that weaken the coil can be reduced in number or eliminated completely, similar to the polyhelix. In addition, closely spaced cooling passages can be attained as in the radial Bitter, thereby reducing or eliminating the power density-limited innermost zone of the polyhelix technique. Thus, high current densities and high power densities can be supported. By combining the water velocity variation attainable by radial cooling with the higher pressure at the inlet end, water velocities up to 30 m s^{-1} can be attained without cavitation [50]. To attain such a velocity in an axially cooled magnet without cavitation would require an outlet pressure of 9 bars [51]. Thus, very high heat transfer coefficients are attainable (equation (6)).

Laurence and Coles built an early monohelix in the early 1960s, as it was a convenient geometry [42, 45]. The technology was heavily used in the 1980s by Weggel at the FBNML [52] and occasionally during the 1990s by Rub in Grenoble [53].

4.2. Second generation inserts: 1978–1987

4.2.1. Nijmegen Ia and Ib. The FBNML at MIT designed and built a superconducting outsert for the High Field Magnet Laboratory of Nijmegen, The Netherlands. The outsert consisted of ventilated double pancakes of highly aspected NbTi composite conductor operating at 4.2 K.

Two inserts were designed and built by Weggel. Both inserts consisted of two series-connected Bitter coils. The first insert was built to provide 25 T in Nijmegen using the 6 MW power supply installed there. The second insert was designed to be tested while the outsert was at MIT and to provide 30 T using 9 MW. This second insert would later be installed in a new outsert at the FBNML (see MIT II below).

The first insert (Ia) used axially cooled Bitter coils. The inner coil used Mg–Zr–Cr–Cu sheet with electrical conductivity equal to 90% of the International Annealed Copper Standard (IACS) and a tensile stress of 500 MPa. The outer coil used pure copper. This magnet was installed at the Nijmegen facility and served as a user facility for several decades.

The second insert (Ib) was a radially cooled Bitter using copper alloy reinforced with stainless steel. The copper was dispersion strengthened with Al_2O_3 with a conductivity of 90% IACS and an ultimate strength of 550 MPa. The steel had strength of 2000 MPa. Axial clamping was provided by iron (magnetic) endplates providing a clamping force of 0.5 MN. The outer coil was hard copper. This was the first truly dc magnet to attain 30 T, however, it served as a user facility only briefly until the delivery of the outsert to Nijmegen [54].

4.2.2. MIT II. In 1981 the FBNML at MIT completed the outsert for their second hybrid magnet. It used the cryostat from the earlier hybrid I, now with a new superconducting magnet using a twisted conductor. Again, highly aspected NbTi multi-filamentary composite was wound into double pancakes and operated at 4.2 K.

The first insert (MIT IIa) was the 30 T version previously tested with Nijmegen's outsert and described above (Nijmegen Ib).

The second insert (MIT IIb), again by Weggel, used a single axially cooled Bitter coil with a 5 cm bore to provide 25 T with 7.3 MW. The conductor was silver bearing copper reinforced with heavily cold-worked stainless steel 301. Tie-rods also served to return the current to the original end of the magnet [55].

Various monohelix inserts were later installed and operated from 1986 to 1992 using Be–Cu, Cr–Cu, 12% Ag–Cu, Nb–Cu, Cu–Al_2O_3 and other alloys (MIT IIc). These versions provided fields as high as 31.8 T in a 33 mm bore [43, 52, 55].

4.2.3. Sendai I. In 1981 the Research Institute for Iron, Steel and Other Metals at Tohoku University, Sendai, Japan began upgrading their old 3.5 MW resistive magnet facility to 8 MW. The centrepiece of this development was the design and construction of three hybrid magnets by Toshiba Corporation [56].

In 1983 the first of the hybrids (Sendai I) was completed. The outsert used layer-wound NbTi without helium ventilation, providing 7.7 T.

The insert was an axially cooled Bitter coil of very small size (outer diameter 185 mm) providing 12.8 T, for a total of 20.5 T. The conductor was copper dispersion-strengthened with Al_2O_3 [57]. This magnet was intended largely as a prototype for developing the technology for the two subsequent magnets described below.

4.2.4. Sendai II. The second hybrid built in Sendai used ventilated NbTi double-pancake coils for the outsert. It provides 7.5 T in a much larger bore (320 mm versus 185 mm) than did Sendai I.

The insert consists of two concentric axially cooled Bitter coils connected in series both electrically and hydraulically. The outer coil used silver-bearing copper. The inner coil was copper dispersion strengthened with Al_2O_3. With 6.7 MW of power it provides 16.1 T, for a total field of 23.6 T [58].

4.2.5. Sendai IIIa and IIIb. The third Sendai hybrid was completed in 1984 (only one year after the first hybrid and three years after the start of the programme). The outsert uses both NbTi and Nb_3Sn wound into double pancakes providing 11.1 T.

Two inserts were designed and built by Toshiba using Schneider-Muntau's version of polyhelix technology and using silver-bearing copper. Insert IIIa uses 12 helices to provide 19.6 T in a 32 mm bore for a total of 30.7 T. Insert IIIb uses 10 helices to provide a total of 27 T in a 52 mm bore [59].

4.2.6. Oxford Ib. In 1987 Jones tested a new insert in a hybrid system at Oxford that provided 20 T with only 2 MW of power. The system used the outsert described previously. The insert was a novel polyhelix concept that was wound from a single continuous conductor [60].

4.2.7. Grenoble I. In 1986 the Grenoble High Magnetic Field Laboratory completed their first hybrid magnet providing 30 T in a 50 mm bore. The outsert consisted of two coils, both of ventilated NbTi operating at 1.8 K (a first). The inner one was layer-wound; the outer one, pancake-wound [61].

The insert was designed and built by Schneider-Muntau. In 1987 the magnet attained a record 31.4 T. The insert consisted of 14 coils. The inner 12 were polyhelix coils, while the outer two were axially cooled Bitter coils [62]. It should be noted that this magnet had a larger bore than the other 30 T class magnets in the world at that time (50 mm versus 30 or 32 mm). It was surpassed nine years later by TML Ib using 50% more power (section 5.3.2).

4.2.8. Nijmegen IIa. In 1987 the Francis Bitter National Magnet Laboratory completed a second hybrid (30 T, 3 cm bore) for the Nijmegen Laboratory. The new outsert used NbTi pancakes and could be operated at either 4.2 or 1.8 K.

The insert, again by Weggel, consisted of two series-connected radially cooled Bitter coils [63].

4.2.9. Hefei. The Institute of Plasma Physics, Academia Sinica in Hefei, China built a 3.2 MW hybrid magnet. The outsert used 2 mm $\times$ 4 mm monolithic NbTi multifilamentary composite wire in an adiabatic configuration. The insert was a single axially cooled Bitter coil designed and built by Gao using copper dispersion-strengthened with Al_2O_3 [64]. It was completed in 1992.

5. Third generation hybrids 1992–present

The start of the third generation of hybrid inserts coincided roughly with the construction of new high-field magnet laboratories in Tallahassee and Tsukuba and a major power upgrade in Grenoble. It is characterized by power levels up to 30 MW and fields in the 35–45 T range. It also saw the

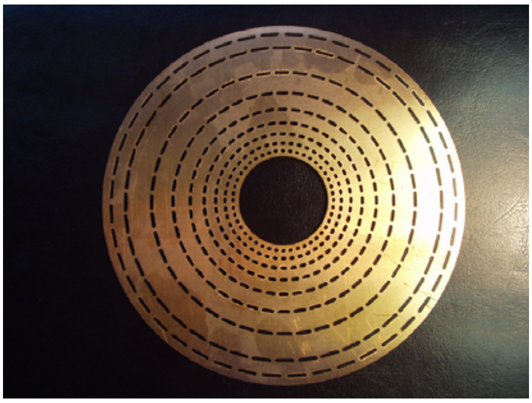

Figure 11. A Bitter disk from MIT with elongated, aligned cooling holes.

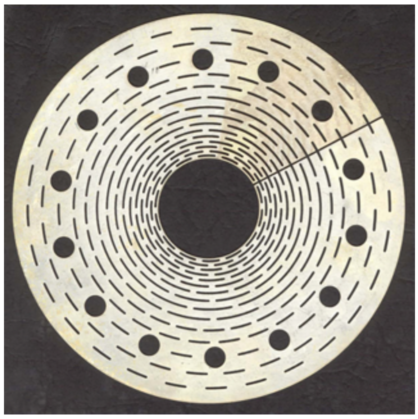

Figure 12. Florida–Bitter disk from Tallahassee with highly elongated, staggered cooling holes.

first use and proliferation of Florida–Bitter and copper–silver hybrid inserts.

5.1. *Florida–Bitter technology*

In 1995 a new resistive magnet was completed at the National High Magnetic Field Laboratory in Tallahassee, Florida by the team of Bird, Bole, Eyssa, Gao and Schneider-Muntau. The magnet provided 30 T in a 32 mm bore using 16 MW of power. The magnet was the first to utilize the new 'Florida–Bitter' technology that has since become the international standard, installed in four of the five largest magnet laboratories worldwide [65]. One measure of the efficiency of Florida–Bitter technology is to note that Carden's 30 T resistive magnet used 30 MW [36]. If we use the simple square-root scaling of equation (4), one might expect a Florida–Bitter magnet using 30 MW to provide 41 T instead of only 30 T.

The Florida–Bitter technology is a substantial improvement to the axially cooled Bitter magnet, combining the reduced stress of polyhelices with the cooling of Bitter magnets. Like a traditional, axially cooled, Bitter magnet, it is constructed of copper alloy sheet with holes for cooling water. The improvement is the subtle yet profound concept of employing the cooling holes for stress management.

A traditional Bitter magnet uses circular holes. Some Bitter magnets use elongated holes aligned as shown in figure 11 [66]. The Florida–Bitter magnet uses highly elongated holes in a staggered grid, as shown in figure 12. By using highly elongated holes, the stress concentrations near the holes are greatly reduced. By placing the holes in a staggered grid, radial stress transmission is reduced almost to that attained by polyhelices. However, by having cooling holes in the conductor, one eliminates the current-density-limited zone associated with polyhelices [67, 68].

Table 3 presents some of the design parameters of the innermost coil of the first Florida–Bitter magnet built: a 30 T, 32 mm bore, 16 MW system in Tallahassee. We compute the mid-plane hoop stress in four ways. (1) First we use Weggel's formula (equation (7)) ignoring the cooling holes entirely. (2) Second, we include the space-factor correction for the cooling holes (note, this does not account for stress concentrations). (3) Third, we compute the stress that would exist in a simple slender ring of a conductor that was completely detached from its neighbours (jBr). (4) Finally, we present the actual hoop stress in the innermost ring of the conductor of the real magnet as computed using a detailed finite element model. We see that the actual stress is only **64%** what it would be in a traditional Bitter magnet and it is 22% less then it would be if there were no cooling holes at all! It is only 12% higher than what could be attained if the innermost ring were completely de-coupled from the rest of the magnet [13].

Table 3. Stress in inner coil of a 30 T Florida–Bitter magnet.

Inner radius (mm)	19
Outer radius (mm)	74
Coil height (mm)	174
Field at inner edge (T)	30.0
Field at outer edge (T)	16.6
Current (kA)	35.0
Power (MW)	4.51
Current density at inner edge (A mm^{-2})	643
Power density at inner edge (A mm^{-3})	12.0
Space factor	0.738
Number of turns	59
Number of disks per turn	7
Disk thickness (mm)	0.40
Insulation thickness (mm)	0.15
Turn thickness (mm)	2.95
Weggel without cooling holes (MPa)	**550**
Weggel stress with cooling holes (MPa)	**746**
Simple ring stress (jBr) (MPa)	**428**
ANSYS stress (MPa)	480

While this technology was first employed in Tallahassee, it has since been used in Tsukuba [13] and Sendai [69] and is being installed in Nijmegen [70].

5.2. *HSHC copper–silver technology*

Most of the hybrid inserts discussed thus far are made of high-strength copper, dispersion-strengthened copper, copper–zirconium, copper–beryllium, or silver-bearing copper (~0.5% Ag). As indicated in sections 2.1 and 2.2, the selection of the material for the construction of a resistive magnet is largely a matter of balancing the need for strength versus the greater cooling required for more resistive materials.

In 1993 Sakai of the Tsukuba Magnet Laboratory developed a new high-strength, high-conductivity alloy of 24% silver in a copper matrix that can have a conductivity of 73% that of pure copper with a strength up to 1000 MPa [71].

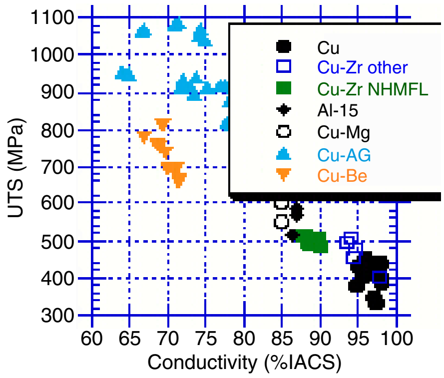

Figure 13. Strength (MPa) versus electrical conductivity as a percentage of the International Annealed Copper Standard (%IACS) for various hybrid insert materials.

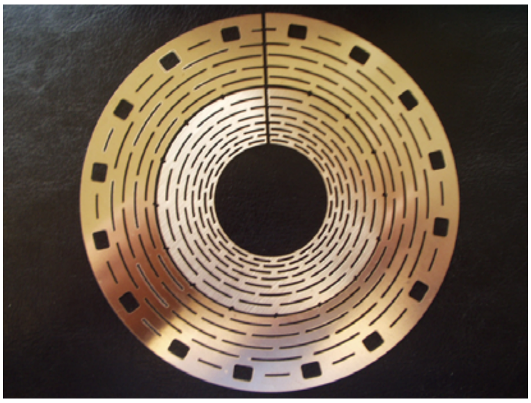

Figure 14. Florida–Bitter disk for a Tsukuba hybrid insert.

Figure 13 presents the strength and conductivity of various alloys used for high field magnets as measured at the NHMFL. One sees that the materials other than the Cu–24% Ag alloy fall close to a line: increasing strength is associated with decreasing conductivity. The Sakai alloy lies substantially above the line; its conductivity is equal that of the Cu–Be alloy, but its strength is greater by a factor of 1.5 or more. This new Cu–24% Ag alloy is a dramatically better material for use in high field resistive magnets and hybrid inserts than the competing materials. Evidence is given both by the plot in figure 11 and by the fact that most of the hybrid inserts built since its development have used it, despite its cost, for the innermost coils.

5.3. Third generation inserts: 1992–present

5.3.1. MIT IIIa, IIIb. The third hybrid installed at MIT (excluding the two built for Nijmegen) was completed in 1991 and attained 33.6 T that year. The outsert consists of an 18-layer Nb_3Sn coil and a 32 double-pancake NbTi coil. It is 'quasi-adiabatic', unlike the earlier hybrids at MIT, which were cryostable [72].

The inserts were designed and built by Weggel using both Cu–Be monohelix technology and the new Cu–Ag sheet metal in a radially-cooled Bitter technology. The insert was later upgraded such that a record 35.2 T was attained in a 32 mm bore in 1994 [73].

5.3.2. Tsukuba Ia, Ib. The National Research Institute for Metals created the Tsukuba Magnet Laboratory in Tsukuba, Japan with a mission to develop high field magnets, both resistive and superconducting. In 1999 the laboratory set what is presently the world record for high field superconducting magnets with 23.5 T [2]. The laboratory started its '40 T class' hybrid project in 1988. In 1994 the Toshiba Corporation completed the first version of the hybrid magnet [74]. The outsert consists of 58 double pancakes operating at 4.2 K stacked in four concentric fully stable coils and provides 14.2 T on-axis. The inner two coils are Nb_3Sn, while the outer two are NbTi. The Nb_3Sn conductor has an intentional gap between one side of the superconducting core and the copper reinforcement/stabilizer [75].

Two insert designs were built; both were polyhelices based largely upon Schneider-Muntau's technology. The main innovation was cutting the inner coils from bar using wire electric discharge machining (EDM).

Ib had a 50 mm bore and consisted of 15 helices. The inner six were of Cu–Cr alloy. The rest were Cu–Al_2O_3. It was successfully tested to a record total field of 32.1 T using 15 MW of power.

Ia had a 30 mm bore and used 18 helices made of copper dispersion-strengthened with Al_2O_3. It was destructively tested at a total field of 35.7 T [74]. Insert Ia was rebuilt and reached 36.5 T later in 1995 [76].

5.3.3. Tsukuba Ic, Id. After receiving a Florida–Bitter resistive magnet from the NHMFL in 1997 [13], the Tsukuba Magnet Laboratory ordered new inserts for their hybrid magnet to be designed and built by Toshiba. The new inserts would abandon the polyhelix technology used for the first set of inserts and would adopt the Florida–Bitter technology (see figure 14) using Cu–24% Ag sheet.

The first new insert (Ic) was tested in 1998 providing up to 31 T in a 52 mm bore during testing and 30 T during routine operation. The second new insert (Id) was tested in September, 1999, providing up to 37.3 T in a 32 mm, a world record at that time. Regular operation of the 32 mm bore version started at 35 T in 2000 [76].

5.3.4. Sendai IIIc and IIId. In 1999 the Sendai Laboratory completed a new pair of inserts for their third hybrid. This time they did not rely upon the Toshiba Corporation, and Motokawa and Awaji led the effort. The new inserts were both Florida–Bitter, copper–silver technology (see figure 15) replacing the previous Al_2O_3 polyhelices. While the fields and bores of the new inserts are the same as those previously reported for the old inserts, the outsert now provides 1 T less than it did for the earlier versions [77].

5.3.5. NHMFL Ia, Ib. The National High Magnetic Field Laboratory in Tallahassee, FL, USA has built the world's first 45 T dc magnet. The outsert is the first and (to date) only cable-in-conduit hybrid outsert. It consists of three nested coils. The inner two are layer-wound of Nb_3Sn cable in a stainless steel conduit. The outer one is 29 double pancakes of NbTi cable in

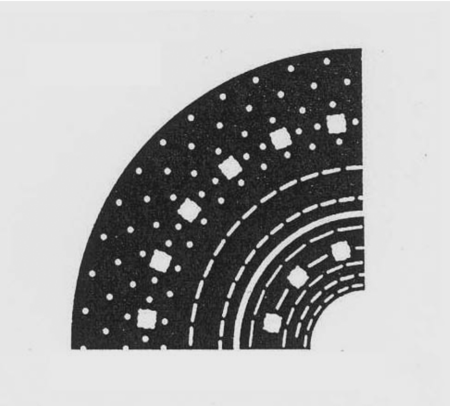

Figure 15. Florida–Bitter disk cooling hole pattern for Sendai IIIc hybrid insert [77]. Reprinted with permission. © 2000 IEEE.

a stainless steel conduit. The coil operates in a bath of 1.8 K helium and carries a current of 10 000 A [78].

The first insert (Ia) was completed in May 1999, when it was tested to 32.5 T without the superconducting outsert. The insert consists of five nested Florida–Bitter coils. The inner three use Cu–Ag alloy, the next two use Cu–Be alloy, the outermost uses Cu–Zr alloy [79].

The combined system was first tested in December 1999 and attained 44 T in a 32 mm bore. There was some slippage of disks in the end turns, as discussed in section 3.2.1. This is a common occurrence in hybrid inserts. The magnet was shut down in December 1999 for scheduled work on the cryogenics system. The insert was modified slightly during this time. On 26 June 2000 the combined system reached its design target of 45.1 T [80].

In July 2000 the superconducting outsert experienced a quench during which the quench protection system malfunctioned. Hence, the 100 MJ of stored energy was dissipated in the innermost coil of the superconductor. The performance of the outsert was degraded, and its operating field has been reduced from 14.2 to 11.4 T [81]. In order to continue to provide 45 T to the user community, the insert required redesign.

Insert Ib was completed and tested on 1 February 2001 to a field of 45.1 T on nine different field sweeps. Not only does the new insert reach the design field of 45 T with the reduced outsert field, it is also the first insert to systematically address the end-turn concerns. This is done by examining the stress state in a half disk that is clamped on one end and free on the other while applying the Lorenz forces appropriate for the end of the coil. By increasing the turn thickness and modifying the shape of the cooling holes in the end turn, sufficiently low stresses and displacements can be attained [31].

A new project has been initiated at the NHMFL to replace the damaged innermost Nb_3Sn coil. The winding line has been constructed at the NHMFL, and cabled wire has been ordered. The outsert may be repaired by 2005 [1].

6. Construction/development

Never content with present capabilities, experimentalists are continuing to request higher fields, and magnet designers are continuing to pursue the technology to provide them. The following are various hybrid magnet projects that are being discussed, under construction or being tested at facilities around the world.

6.1. New technologies: high homogeneity

Historically, the primary use of hybrid magnets has been for experiments requiring very intense flux densities. Presently, there is a move afoot to design hybrid magnets with high field uniformity (homogeneity) as well.

High-field, low-resolution NMR has been performed in resistive magnets for decades [42]. In 1998 a 25 T resistive magnet was completed that has a field uniformity of 12 ppm over a 10 mm diameter spherical volume (DSV). To attain such uniformity, one starts by introducing splits or axial current density grading to reduce the z^2 term of the field. The next term to appear is the z term due to the thermal gradient in the coil. Adjusting the coils axially can compensate this. The next terms of importance are not the z^4 and z^6 terms associated with axisymmetric coils, but the x and y terms arising from manufacturing tolerances. They can be up to 50 ppm over a 10 mm DSV. At the NHMFL these terms were corrected via ferroshimming. Potentially one could use water-cooled resistive shims [82].

The desire in the scientific community to perform NMR experiments at higher fields continues to drive development. Recent NMR experiments above 16 T have enabled one to: locate protons in hydrogen bonds and study their dynamics, specify the mutual arrangements of aromatic moieties, detect chain order of synthetic macromolecules and probe the mechanism of generating inorganic/organic hybrid materials [83].

Presently, '. . . such diverse technological challenges as efficient fuel cells, photonic sensors & devices, or gene delivery systems all require transport of electrons, holes, protons, or other ions. This transport critically depends on the arrangement of the building blocks of the material relative to each other and their mobility on different scales of length and time. Even more informative for establishing structure/function relationships is the direct observation of functional carriers themselves. Solid state NMR spectroscopy has the potential of becoming one of the key methods to provide this vital information' [83].

This interest in performing NMR experiments at high field has led researchers to conduct experiments at fields as high as 44.5 T [84]. The NHMFL is proposing to build an NMR hybrid magnet to provide 35 T with only 10 MW of power (see section 6.2.5).

6.2. New inserts

6.2.1. Sendai IV. Tohoku University has undertaken the task of building the world's first cryogen-free hybrid outsert. The magnet will replace the old Sendai II hybrid. The old insert will continue to be used. The new superconducting coil uses Nb_3Sn wire reinforced/stabilized with high strength Cu–Nb wire and will provide 8 T [85]. The new outsert has been completed and tested. The innermost Nb_3Sn coil did not work properly. The system was energized without that coil to 20 T. The defective coil will be replaced [86].

6.2.2. Tsukuba Ie. The Tsukuba Magnet Laboratory has abandoned their practice of buying hybrid inserts from the Toshiba Corporation, and a staff member (Asano) has designed a new insert intended to reach 38 T. The new insert uses Florida–Bitter, copper–silver technology and is expected to be tested late in 2002 [87].

6.2.3. Grenoble II. The Grenoble Magnet Laboratory has built 30 T, 50 mm bore resistive magnets making their hybrid obsolete [88, 89]. They have removed their 30 T hybrid (Grenoble I) and are building a new 40 T version (Grenoble II) to be installed in the same space.

The new outsert will consist of three concentric, layer-wound coils using copper-stabilized, NbTi Rutherford cable with a stainless steel insert to reduce coupling currents and to provide mechanical strength and stiffness. It will operate at 1.8 K. It is notable for having a very large bore (1.1 m compared with 0.3–0.5 m at other facilities). This is to provide generous space for the 24 MW of power available for the insert.

The outsert is also intended to withstand an insert trip without quench. To help accommodate this requirement, the outsert includes a novel feature: a cold-worked oxygen-free copper tube installed at the inner diameter of the superconducting coils. When the insert trips, the magnetic flux transient experienced by the superconducting coils should be slowed from 0.6 to 5.0 s by the presence of the high conductivity cylinder [90].

The new insert will consist of two Bitter coils of Cu–Ag consuming 12 MW of power [91] and 14 helices of Cu–Zr also consuming 12 MW of power. The magnet has been assembled and cool-down of the outsert started in April 2004 [92].

6.2.4. NHMFL Ic. The NHMFL in Tallahassee is presently replacing the innermost Nb_3Sn coil of its superconducting outsert. When that is complete, a new insert will be built using the full 40 MW of our dc supply to pursue a goal of 50 T. The insert technology is likely to be Florida–Bitter or an improvement thereof.

6.2.5. NHMFL II. The NHMFL in Tallahassee, FL intends to build a new hybrid primarily for NMR and other magnetic resonance measurements. The outsert will likely utilize forced-flow cable-in-conduit technology with a Nb_3Sn cable carrying 20 kA while providing 15 T on-axis. The insert will likely consist of four Florida–Bitter coils made of Cu–Ag alloy sheet. A novel feature of this system is the intention to connect the resistive and superconducting coils electrically in series. Such a configuration eliminates the need for a separate power supply for the outsert and reduces the margin required in the outsert to accommodate insert trips and outsert only operation.

6.2.6. Nijmegen IIb. The Nijmegen magnet laboratory is building a new high field facility and is installing Florida–Bitter magnets to provide fields up to 33 T. The laboratory will relocate the old Nijmegen II hybrid to the new facility and is considering building a new insert for the 10.5 T outsert. By using Florida–Bitter technology, Cu–Ag sheet metal and 20 MW of power, preliminary calculations indicate 40 T may be available [93].

6.2.7. Brookhaven National Laboratory. Researchers at Brookhaven National Laboratory have proposed building a 20 T hybrid magnet with a 14 T outsert made of cable-in-conduit-conductor and a 6 T insert using a hollow conductor or Bitter magnet technology. To attain an extended lifetime of the magnet despite the high radiation environment, BNL may use a hollow conductor so that the insulation stays dry [26].

7. Conclusions

We have seen that the challenges facing the designer of a hybrid insert are legion. To attain high field one needs high engineering current densities (up to 700 A mm^{-2}). The high current densities in a normal metal result in high power densities (up to 13 W mm^{-3}), which require very closely spaced cooling channels with high-velocity coolant (preferably water). The presence of high current densities and high magnetic fields gives rise to Lorenz forces that result in hoop stresses at the mid-plane, but bending stresses can be present near the ends of the coil. The cooling channels usually introduce stress concentrations in the conductor.

We see that over the past thirty years various technologies have been incorporated into hybrid insert designs. The earliest magnets built in the early 1970s used polyhelices, axially cooled, and radially cooled Bitter magnets. Through the late seventies and early eighties, no new polyhelix magnets were built while several new Bitter magnets were delivered. In the mid-eighties the polyhelix was revived due largely to the work of Schneider-Muntau in Grenoble, and polyhelix hybrid inserts were built in Sendai, Oxford, Grenoble and Tsukuba between 1985 and 1996. In the late eighties Weggel at MIT developed the monohelix technology. In the mid-nineties the Florida–Bitter technology was developed in Tallahassee, and Florida–Bitter inserts were installed in magnets in Tsukuba, Sendai, Tallahassee and are under consideration in Nijmegen.

The Florida–Bitter magnet is a type of Bitter magnet in which the shape and spacing of the cooling holes are optimized (exploited) to manage the stress state. The result can be lower peak stress than what would be attained without any holes. In this way, the Florida–Bitter technology can be thought of as having the ample cooling and ease of construction of a traditional Bitter magnet, but the reduced stresses of a polyhelix. Note, the Florida–Bitter magnet does not have the cooling limitations of the polyhelix but it also does not enjoy continuous helix construction.

The future looks promising as several new inserts in the 40–50 T range are in construction, design and proposal stages. As we consider the next steps in this field, it is appropriate to recall the words of Hudson, Hanley and Carden after completing Oxford Ia in 1975:

'Whilst the next generation of hybrid magnets will perhaps become increasingly ambitious in respect of the design of the superconducting section, problems associated with the inner magnet being exposed to increasingly higher stress levels will be a dominant factor in dictating the overall efficiency of the system' [94].

They are certainly as true today as they were then.

Acknowledgments

The author is greatly indebted to the many senior resistive magnet designers who have contributed to the author's education. Primary among them are Yehia Eyssa, Hans Schneider-Muntau and Robert Weggel, the last of whom also provided a great deal of historical perspective in proof-reading this manuscript. In addition, the author wishes to express his appreciation to Scott Bole who has played a leading role in the mechanical design of all of the resistive magnets (and hybrid inserts) in Tallahassee and to Youri Viouchkov who provided figures for this publication.

This work was supported in part by the National Science Foundation under Grant DMR 0084173.

References

[1] Miller J R 2002 The NHMFL 45 T hybrid magnet system: past, present, and future *IEEE Trans. Appl. Supercond.* **13** 1385–90
[2] Kiyoshi T *et al* 2000 Generation of 23.4 T using two Bi2212 insert coils *IEEE Trans. Appl. Supercond.* **10** 472–7
[3] Bird M D *et al* 1996 Design of a poly-Bitter magnet at the NHMFL *IEEE Trans. Magn.* **32** (July) 2542–5
[4] Li L *et al* 2000 High performance pulsed magnets with high strength conductors and high modulus internal reinforcement *IEEE Trans. Appl. Supercond.* **10** (1)
[5] Vaghar M R *et al* 2000 Roads to 100 T pulsed magnets *IEEE Trans. Appl. Supercond.* **10** (1)
[6] Bykov A I *et al* 2001 VNIIEF achievements on ultra-high magnetic fields generation *Physica* B **294/295** 574–8
[7] Wood M F and Montgomery D B 1966 Combined superconducting and conventional magnets *Colloques Internationaux du Centre National de la Recherche Scientifique (Grenoble, 1966)*
[8] Montgomery D B and Weggel R J 1969 *Solenoid Magnet Design: The Magnetic and Mechanical Aspects of Resistive and Superconducting Systems* (New York: Wiley) section 2.3
[9] Kays W M and Crawford M E 1993 *Convective Heat and Mass Transfer* (New York: McGraw-Hill) chapter 14
[10] Lide D R (ed) 1994 *CRC Handbook of Chemistry and Physics* (Boca Raton, FL: CRC Press) pp 12–40
[11] Thomas L C 1992 *Heat Transfer* (Englewood Cliffs, NJ: Prentice-Hall)
[12] Sakai Y 1994 High-strength and high-conductivity Cu–Ag alloy sheets: new promising conductor for high-field Bitter coils *IEEE Trans. Magn.* **30** 2114–7
[13] Bird M D *et al* 1998 NRIM/NHMFL joint development of a 30 T magnet *Proc. 15th Int. Conf. on Magnet Technology* (Beijing: Science Press) pp 664–7
[14] Montgomery D B and Weggel R J 1969 *Solenoid Magnet Design: The Magnetic and Mechanical Aspects of Resistive and Superconducting Systems* (New York: Wiley) section 5.1
[15] Hudson P A 1972 Magnet technology at the Mullard Cryomagnetic Laboratory of the Clarendon Laboratory, Oxford *Proc. 4th Int. Conf. on Magnet Technology (Brookhaven, 1972)* (CONF-720908) pp 444–9
[16] Schneider-Muntau H-J, Picoche J C, Rub P and Vallier J C 1982 The generation of high magnetic fields in Grenoble—installations and magnets *Application of High Magnetic Fields in Semiconductor Physics (Grenoble, 1982)*
[17] Leupold M J *et al* 1985 Testing of a 1.8 K hybrid magnet system *Proc. 9th Int. Conf. on Magnet Technology (Zurich, 1985)* (Villigen, Switzerland: Swiss Institute for Nuclear Research) (isbn 3-907988-00-6) pp 215–8
[18] Picoche J C, Rub P and Schneider-Muntau H-J 1979 The high field magnet laboratory of Grenoble *J. Magn. Magn. Mater.* **11** 308–16
[19] Weggel R J and Montgomery D B 1972 Hybrid magnets *Proc. 4th Int. Conf. on Magnet Technology (Brookhaven, 1972)* pp 18–28
[20] de Klerk D 1965 *The Construction of High Field Electromagnets* (Buckinghamshire: Newport Instruments) chapter 4
[21] Kolm H H 1961 *Nature* **192** 299
[22] Brown R L 1962 *Thermonuclear Division Semiannual Progress Report* ORNL-3392 pp 67–73
[23] Innocenti P G and Morpurgo M 1964 *Design and Construction of a 100 kG dc Magnet* (Geneva: CERN 64-23, MSC and NPA Division)
[24] Bitter F 1962 Water cooled magnets *Proc. Int. Conf. on High Magnetic Fields* (Cambridge, MA: MIT Press) pp 85–99
[25] Weggel R J 2002 Conceptual design of pion-capture magnets of up to 15 cm bore and 20 T peak field *IEEE Trans. Appl. Supercond.* **12** 487–91
[26] Bitter F 1936 The design of powerful electromagnets: part II—the magnetizing coil *Rev. Sci. Instrum.* **7** (December) 482–8
[27] Bitter F 1939 The design of powerful electromagnets: part IV—the new magnet lab at M.I.T. *Rev. Sci. Instrum.* **10** (December) 373–81
[28] Montgomery D B and Weggel R J 1969 *Solenoid Magnet Design: The Magnetic and Mechanical Aspects of Resistive and Superconducting Systems* (New York: Wiley) section 5.4
[29] Carden P O 1970 The design and construction of a Bitter solenoid having a 26 cm diameter bore and generating 16.5 tesla with 26 MW of power *Proc. 3rd Int. Conf. on Magnet Technology* (Germany: DESY) pp 630–54
[30] Mulhal B E 1972 Bitter magnets for 20 T *Proc. 4th Int.Conf.onMagnet Technology (Brookhaven, 1972)* pp 360–2
[31] Dixon I R, Bird M D and Bole S 2002 End Effects in the NHMFL 45 T hybrid resistive insert *IEEE Trans. Appl. Supercond.* **12** (1)
[32] Bettis E S 1959 Magnetic coil design for DCX-1 *Proc. Symp. on Magnetic Field Design in Thermonuclear Research* ORNL-2745 *(Gatlinburg, TN, 1959)* pp 8–9
[33] Giauque W F and Lyon D N 1960 Design of a 100 kilogauss 4 inch core solenoid for continuous operation *Rev. Sci. Instrum.* **31** 374–90
[34] Wood M 1962 The high-field magnets at Oxford *Proc. Int. Conf. on High Magnetic Fields* (Cambridge, MA: MIT Press) pp 387–92
[35] Carden P O 1972 Testing the ANU 30 T high field magnet at Canberra *J. Phys. E: Sci. Instrum.* **5** 667–8
[36] Carden P O 1974 The ultimate possibilities of quasi-continuous high field electromagnets *J. Phys. E: Sci. Instrum.* **7** 750–6
[37] Carden P O 1972 Design and construction of the inner solenoid of the ANU 30 T electromagnet *J. Phys. E: Sci. Instrum.* **5** 663–6
[38] Schneider-Muntau H-J 1981 Polyhelix magnets *IEEE Trans. Magn.* **17** 1775–8
[39] Schneider-Muntau H-J 1982 Generation of very high continuous fields by polyhelix and polyhelix hybrid magnets *IEEE Trans. Magn.* **18** 1565–70
[40] Schneider-Muntau H-J and Prestemon S 1992 Poly-Bitter magnets *IEEE Trans. Magn.* **28** 486–8
[41] Trophime C *et al* 2002 Magnet calculations at the Grenoble High Magnetic Field Laboratory *IEEE Trans. Appl. Supercond.* **12** 1483–7
[42] Montgomery D B and Weggel R J 1969 *Solenoid Magnet Design: The Magnetic and Mechanical Aspects of Resistiveand Superconducting Systems* (New York: Wiley) section 4.4
[43] Weggel R 2003 private communication to Bird M

[44] Weggel R J and Montgomery D B 1972 Hybrid magnets *Proc. 4th Int. Conf. On Magnet Technology (Brookhaven, 1972)* pp 18–28
[45] Laurence J C and Coles W D 1965 Design, construction and performance of cryogenically cooled and superconducting electromagnets *Proc. Int. Symp. on Magnet Technology (Stanford, 1965)* (Springfield, VA: Stanford) CONF-650922) pp 574–87
[46] Hudson P A, Hanley P E and Carden P O 1975 Exceptional aspects of high power resistive solenoids in relation to their use in hybrid magnet systems *Proc. 5th Int. Conf. on Magnet Technology (Rome, 1975)* (Frascati, Italy: Laboratori Nazionali del CNEN) pp 414–8
[47] Krasnoperov E P 2002 private communication to Bird M D
[48] Chermnykh P A *et al* 1975 25 tesla hybrid magnet *IEEE Trans. Magn.* **11** 519–20
[49] Keilin V 2002 private communication to Bird M D
[50] Weggel R J *et al* 1985 The radially-cooled continuous helix: design study and fabrication of test coil *Proc. 9th Int. Conf. on Magnet Technology (Zurich, 1985)* (Villigen, Switzerland: Swiss Institute for Nuclear Research) pp 439–42
[51] Potter W C and Foss J F 1982 *Fluid Mechanics* (Great Lakes Press) section 5.6 pp 265–7
[52] Weggel R J, Holmes C K and Hale D 1992 The monohelix: (1) five years of operation at the FBNML and (2) finite element stress analysis *IEEE Trans. Magn.* **28** 501–4
[53] Rub P and Joss W 1996 A new type of radially cooled helices designed for a 25 T magnet *IEEE Trans. Magn.* **32** 2570–3
[54] Leupold M J, Weggel R J and Iwasa Y 1978 Design and operations of 25.4 and 30.1 tesla hybrid magnet systems *Proc. 6th Int. Conf. on Magnet Technology* (Bratislava: ALFA) pp 400–5
[55] Leupold M J *et al* 1981 30 tesla hybrid magnet facility at the Francis Bitter National Magnet Laboratory Massachusetts Institute of Technology *IEEE Trans. Magn.* **17** 1779–82
[56] Nakagawa Y 1981 A design of high-power water-cooled magnet suitable for hybrid magnet *IEEE Trans. Magn.* **17** 1786–9
[57] Nakagawa Y *et al* 1984 Hybrid magnet project at Tohoku University *J. Physique Coll.* **45** C1 23–8
[58] Nakagawa Y *et al* 1985 Present status of hybrid magnets at Tohoku University *Proc. 9th Int. Conf. On Magnet Technology (Zurich, 1985)* (Villigen, Switzerland: Swiss Institute for Nuclear Research) pp 424–7
[59] Takano H *et al* 1985 Design, fabrication and test operation results of polyhelix coil for the Tohoku hybrid magnet *Proc. 9th Int. Conf. on Magnet Technology (Zurich, 1985)* (Villigen, Switzerland: Swiss Institute for Nuclear Research) pp 219–22
[60] Jones H, Whitworth H M and Sherratt G 1988 The uprate of the Oxford hybrid magnet to 20 tesla *IEEE Trans. Magn.* **24** 1074–7
[61] MPI-CNRS 1981 A 30 tesla hybrid magnet with 5 cm bore:aFrench–German project *IEEE Trans. Magn.* **17** 1783–5
[62] Schneider-Muntau H-J and Vallier J C 1988 The Grenoble hybrid magnet *IEEE Trans. Magn.* **24** 1067–9
[63] Leupold M J *et al* 1985 Testing a 1.8 K hybrid magnet system *Proc. 9th Int. Conf. on Magnet Technology (Zurich, 1985)* (Villigen, Switzerland: Swiss Institute for Nuclear Research) pp 215–8
[64] Gao B J *et al* 1985 The hybrid magnet project in Hefei *Proc. 9th Int. Conf. on Magnet Technology (Zurich, 1985)* (Villigen, Switzerland: Swiss Institute for Nuclear Research) pp 223–5
[65] Bird M D *et al* 1996 The world's first 27 T and 30 T resistive magnets *IEEE Trans. Magn.* **32** 2444–9
[66] Nakagawa Y *et al* 1983 Detailed analysis of a Bitter-type magnet *Japan. J. Appl. Phys.* **22** 1020–4
[67] Gao B J *et al* 1996 A new concept in Bitter disk design *IEEE Trans. Magn.* **32** 2503–6
[68] Eyssa Y M *et al* 1998 Design and stress analysis of Florida–Bitter magnets *Proc. 15th Int. Conf. on Magnet Technology* (Beijing: Science Press) pp 660–3
[69] Motokawa M *et al* 2000 Construction of large scale Bitter magnet and its application to crystal growth in levitating water *IEEE Trans. Appl. Supercond.* **1** 905–8
[70] Perenboom J *et al* 2001 The new 20 MW high magnetic field installation at the University of Nijmegen *Physica* B **294/295** 529–34
[71] Sakai Y, Inoue K and Maeda H 1994 High-strength and high-conductivity Cu–Ag alloy sheets: new promising conductor for high-field Bitter coils *IEEE Trans. Magn.* **30** 2114–7
[72] Iwasa Y *et al* 1994 Operation of hybrid III as a facility magnet *IEEE Trans. Magn.* **30** 2162–3
[73] Weggel R J 2003 private communication to Bird M D
[74] Inoue K *et al* 1996 First test operation of 40 tesla class hybrid magnet system *IEEE Trans. Magn.* **32** 2450–3
[75] Hanai S *et al* 1996 Development of superconductor and magnet design of 40 T class hybrid magnet *IEEE Trans. Magn.* **32** 2486–9
[76] Asano T *et al* 2001 Resistive insert magnet for a 37.3 T hybrid magnet *Physica* B **294/295** 635–8
[77] Motokawa M *et al* 2000 Construction of large scale Bitter magnet and its application to crystal growth in levitating water *IEEE Trans. Appl. Supercond.* **10** (1)
[78] Miller J R *et al* 1994 An overview of the 45 T hybrid magnet system for the new National High Magnetic Field Laboratory *IEEE Trans. Magn.* **30** 1563–71
[79] Bird M D *et al* 2000 Test results and potential for upgrade of the 45 T hybrid insert *IEEE Trans. Appl. Supercond.* **10** 439–42
[80] Bird M D *et al* 2001 The 45 T hybrid insert: recent achievements *Physica* B **294/295** 639–42
[81] Miller J R *et al* 2003 Analysis of observations of the NHMFL 45 T hybrid magnet system *Cryogenics* **43** 141–52
[82] Bird M D and Gan Z 2002 Low resolution NMR magnets in the 23 to 35 T range at the NHMFL *IEEE Trans. Appl. Supercond.* **12** 447–51
[83] Spiess H W 2001 NMR spectroscopy *European White Book on Fundamental Research in Materials Science* (Munich: Max-Planck-Society) pp 263–5
[84] Vonlanthen P *et al* 2002 High-magnetic-field NMR studies of $LiVGe_2O_6$: a quasi-one-dimensional spin $S = 1$ system *Phys. Rev.* B **65** 213–4
[85] Watanabe K *et al* 2002 Construction of the cryogen-free 23 T hybrid magnet *IEEE Trans. Supercond.* **12** (1)
[86] Watanabe K *et al* 2003 First performance test of the cryogen-free hybrid magnet *IEEE Trans. Appl. Supercond.* **13** 1632–5
[87] Kiyoshi T (of TML) 2002 private communication to Bird M D (of NHMFL)
[88] Aubert G *et al* 2000 The 20 MW–50 mm bore diameter magnet of the Grenoble High Magnetic Field Laboratory *IEEE Trans. Appl. Supercond.* **10** 455–7
[89] Bird M D *et al* 1998 The NHMFl/GHMFL resistive magnet collaboration *Proc. 15th Int. Conf. on Magnet Technology* (Beijing: Science Press) pp 642–4
[90] Bonito-Oliva A 2000 The 8 T, 1.1 m bore superconducting solenoid for the 40 T hybrid magnet of the Grenoble High Magnetic Field Laboratory *IEEE Trans. Appl. Supercond.* **10** 432–8
[91] Debray F and Egorov K 2000 *Empilages Bitter de l'Hybride 20 MW du LCMI* Grenoble High Magnetic Field Laboratory document ENR 297 BI-04 A
[92] Joss W 2004 private communication to Bird M D
[93] Wiegers S 2003 private communication to Bird M D
[94] Hudson P E, Hanley P E and Carden P O 1975 Exceptional aspects of high power resistive solenoids in relation to their use in hybrid magnet systems *Proc. 5th Int. Conf. Magnet Technology (Rome, 1975)* (Frascati, Italy: Laboratori Nazionali del CNEN) pp 414–7